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14. ABSTRACT

Langmuir circulation (LC) and wave breaking are turbulent processes driven by wind and surface waves that are critical in mixing of the ocean surface layer. The effects of LC and breaking waves on upper ocean turbulence are poorly understood, partly because of their mutual entanglement and their interactions with turbulence generated by shear and buoyancy. Utilizing turbulence measurements and a numerical model, we undertake a systematic comparison between observations and simulations of the wave-influenced surface boundary layer. Data sets obtained from the Surface Waves Process Program, the Coastal Mixing and Optics Experiment, and the Coupled Boundary Layers and Air-Sea Transfer experiment provide unique turbulence observations for a wide range of sea and wind conditions. The numerical model is based on a novel large eddy simulation (LES) that incorporates turbulent processes due to LC, buoyancy, shear, and breaking waves, while satisfying the conservation of momentum and energy. Research objectives include quantitative estimates of LC and breaking wave effects in terms of turbulence statistics for a wide range of wind and wave conditions. This work is an important step towards physics-based parameterizations of upper ocean turbulence, which are needed to improve numerical models of weather and climate.

15. SUBJECT TERMS
Upper ocean processes, mixed layer, Langmuir circulation, surface waves

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The effect of Langmuir circulation and breaking waves on subsurface turbulence for realistic wind and wave conditions

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LONG-TERM GOALS

- To understand the role of surface gravity waves and wave-induced processes such as Langmuir circulation, in upper ocean turbulence.
- To develop physics-based turbulence parameterizations that are applicable for a wide range of wind and sea states.

OBJECTIVES

- To configure and run a Large Eddy Simulation (LES) incorporating complex, sea state dependent wave fields to examine turbulence dynamics under a wide range of realistic wind and wave conditions.
- To compare turbulence characteristics obtained from observations and LES to quantify the effect of Langmuir circulation on upper ocean turbulence and mixing.

APPROACH

Our approach employs a Large Eddy Simulation (LES) model based on the work by Sullivan et al. (2007). This model includes the dynamical effects of wave-averaged boundary layer currents, which lead to Langmuir circulation (LC), as well as a stochastic representation of impulses and energy fluxes due to a breaking wave field. The LC effects are modeled in the LES based on the Craik-Leibovich equations (Craik & Leibovich, 1976). We evaluated a more realistic incorporation of a random distribution of breaking waves in the LES (see Tasks Completed) to take advantage of recent advances

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in wind-wave coupling theory (Kukulka et al., 2007, Kukulka & Hara 2008a,b), but this approach did not yield publishable results at the completion of the project.

Available observations include the Surface Waves Process Program (SWAPP, Plueddemann et al., 1996), the Coastal Mixing and Optics experiment (CMO, Dickey & Williams, 2001), and the Coupled Boundary Layers and Air-Sea Transfer experiment (CBLAST, Edson et al., 2007). These data sets are invaluable for our study because they employed instrumentations especially designed to detect LC, and provide size distribution and velocity variance estimates of subsurface coherent features (Smith 1992, Plueddemann et al., 1996), which are compared to LES results. Furthermore, all data sets provide wind stress, heat flux estimates, and two dimensional wave height spectra that are crucial in defining the environmental conditions. Investigation of the SWAPP data set yielded published results at the completion of the project, while initial investigations of CMO and CBLAST have provided intriguing results that motivate further study.

TASKS COMPLETED

We have implemented new subroutines for the LES in order to incorporate time varying wind stress, heat flux, and wave data, which are input at each computational time step during the simulation. These advances were critical to the unique and successful simulation of observations. High resolution numerical simulations forced by observed surface forcing were carried out on multi-core processor computers to provide a direct comparison between observations and LES for a LC growth event (Kukulka et al., 2009; Kukulka et al. 2010). We focused on a single wind event from SWAPP (Plueddemann et al., 1996), for which observed conditions closely resembled the idealized conditions often assumed in LES.

The LES model has also been modified to include wind stress and Stokes drift vectors for arbitrary directions. Further work on the LES included incorporation of complex, sea state dependent wave height spectra and evaluation of the estimated short-wave height spectrum and the distribution of breaking waves based on the new coupled wind and wave model (Kukulka & Hara, 2008a, b) in conjunction with estimates from the few available observations.

RESULTS

We have shown that the evolution of cross-wind velocity variance and spatial scales, as well as the rate and extent of mixed layer deepening, are only consistent with observations if LC effects are included in the model (Fig. 1&2; Kukulka et al., 2009). As in the investigation by Gerbi et al. (2009), a TKE budget analysis of our LES with LC, but without breaking waves, revealed a boundary layer structure with distinct differences from a rigid lid boundary layer (Kukulka et al., 2010), suggesting that TKE production through Stokes drift shear can play a significant role in TKE budgets for realistic ocean conditions. These results offer a validation of the LES approach to understanding LC dynamics, and clearly demonstrate the importance of LC in ocean surface layer mixing.

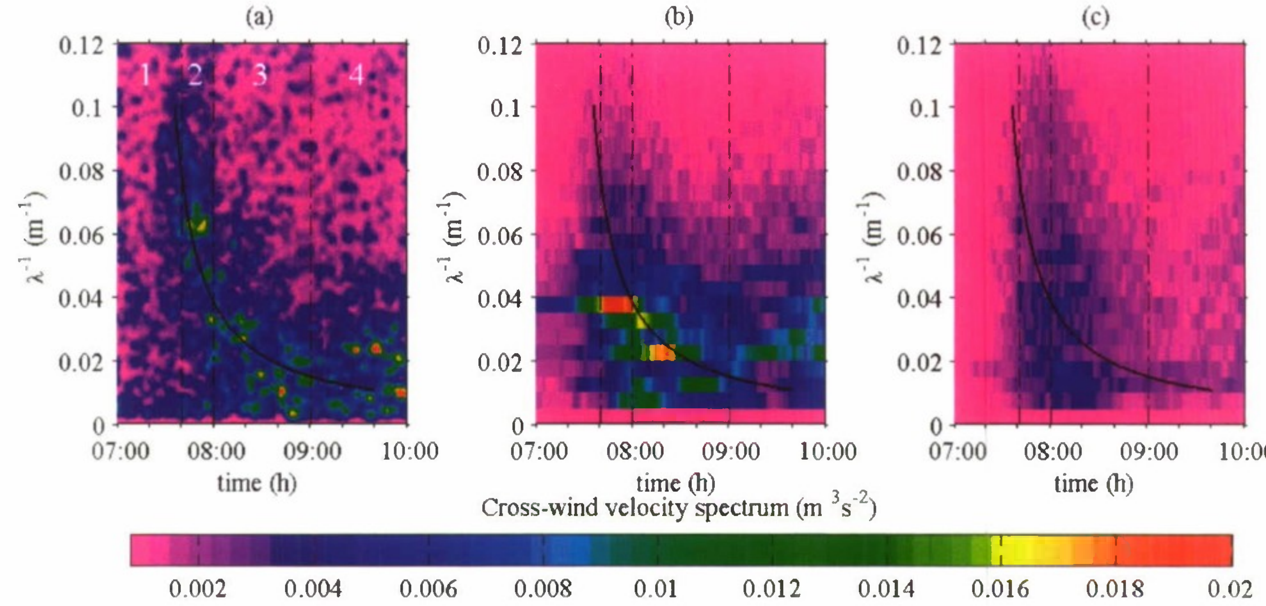

Figure 1. Evolution of cross-wind velocity spectra from observations (left), and from simulations with (center) and without (right) Langmuir circulation. The solid black line corresponds to a length scale increase of 40 mh^{-1}. λ^{-1} is the wavelength (inverse wavenumber). Dashed-dotted lines separate four LC development phases. Observations and simulations with LC show a spectral peak and increasing wavelength with time. Simulations without LC do not show a spectral peak.

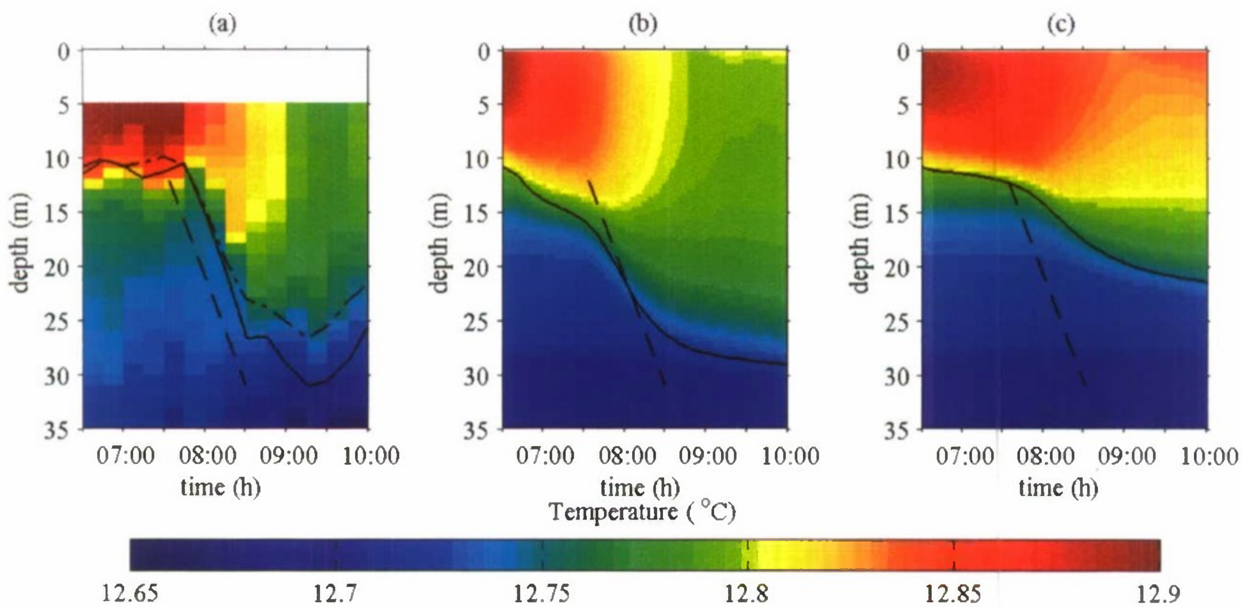

Figure 2. Evolution of temperature profiles: observations (left), simulations with (center) and without (right) Langmuir circulation. The mixed layer depth (MLD, solid line) increases more greatly in the LC case. The observed rate of mixed layer deepening has been previously estimated as 20mh^{-1} (dashed lines at the identical time depth locations in each panel). The dash-dotted line in (a) shows less accurate MLD estimates based on the VMCM data with coarser vertical resolution.

Examination of the LES results in the context of the turbulent kinetic energy (TKE) balance allowed depiction of a typical LC flow structure and identification of fundamental in mixing between shear driven turbulence and turbulence with LC (Kukulka et al., 2010). For shear-driven mixing, TKE is produced by Kelvin-Helmholtz (KH) instabilities, is largest near the surface, and decreases steadily to near zero at the mixed layer base (Fig. 3, left panel). With LC, shear production of TKE shows a minimum in the upper 1/3 of the mixed layer, where TKE production is dominated by Stokes drift shear, and has a secondary peak near the mixed layer base (Fig. 3, right panel). LC plays a key role in this producing this structure, transporting horizontal momentum downward and enhancing KH instabilities near the mixed layer base, which efficiently erodes the thermocline. At the same time, KH instabilities inject cold water from the thermocline into the mixed layer, where LC currents act to enhance advective temperature transport. Thus, LC and shear KH work intimately together to facilitate the mixed layer deepening process.

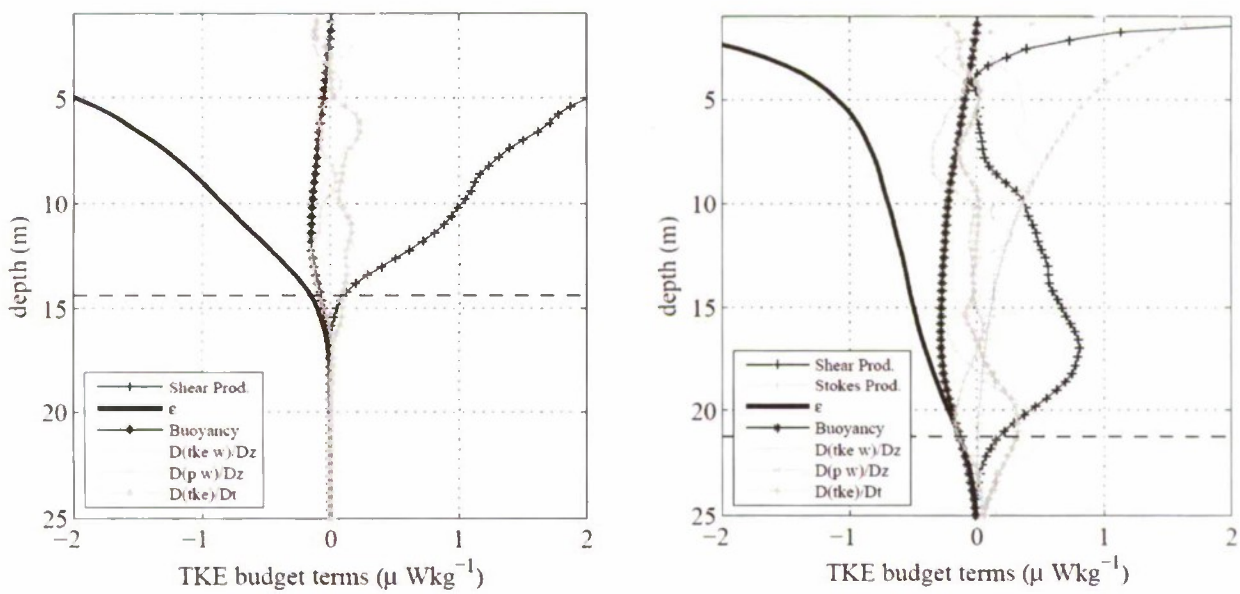

Figure 3. Vertical profiles of terms in the turbulent kinetic energy (TKE) balance from the LES without (left) and with (right) Langmuir circulation. The terms are shear production (black line with pluses), dissipation (thick black line), buoyancy flux (black line with asterisks), vertical divergence of TKE advection (gray line), vertical divergence of pressure work (gray line with crosses), and temporal rate of change of TKE (gray line with asterisks). The horizontal black dashed line indicates the mixed layer depth.

Of interest to the mixed layer modeling community is that LC and the mechanism described in this study could provide a physical foundation for one-dimensional ocean column models with a slab mixed layer (e.g, Price et al. (1986)). These "slab models" prescribe a completely homogenized mixed layer with shear concentrated at the mixed layer base and deepening controlled primarily by shear instability. Although neither of the simulations are truly slab like, the characteristics of the mixed layer are closer to a slab approximation for the LES with LC than with shear-driven mixing alone.

Having demonstrated that LC are critical to mixed layer homogenization and deepening, we would expect one-dimensional mixed layer models should generally depend on surface gravity wave effects as well as wind forcing. In our study, it was possible to collapse terms in the TKE budget for different times during the mixed layer deepening event by scaling with the cross-wind velocity anomaly U (representative of LC strength) and the mixed layer depth. Since U is expected to scale with both wind stress and Stokes drift (Kukulka et al., 2010), wind and wave forcing were included implicitly in the scaling. An open research question is how mixed layer models can be improved by including surface wave properties explicitly (see, e.g., discussion by Li and Garrett (1997)).

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PUBLICATIONS

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